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Charged Higgs Mass Limits from the $\tau^- \to \nu_\tau K^-$ and $K^- \to \bar{\nu}_l l^-(\gamma)$ Branching Fractions

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Abstract

From an analysis of the current world averages of the $K^- \to \bar{\nu}_l\, l^-(\gamma)$ and $\tau^- \to \nu_\tau\, K^-$ branching fractions, we derive, within the framework of type II Higgs doublets models such as the Minimal Supersymmetric Extension of the Standard Model, $\tan\beta/m_H < 0.21$ GeV^{-1}at a 90% confidence limit.

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1 Introduction

The two Higgs doublet model represents one of the simplest extensions to the minimal Standard Model, and is also of interest in the context of supersymmetric models, which require the introduction of at least two Higgs doublets to allow for spontaneous symmetry breaking. The Minimal Supersymmetric Extension of the Standard Model (MSSM) is one of the more popular examples of such a model, and predicts the existence of five Higgs bosons, three of which are neutral, and two of which are charged (H^+ and H^-). The ratio of the vacuum expectation values of the two Higgs fields is an additional parameter in this model, and is referred to as $\tan\beta$.

The most stringent previous indirect limit on the mass of the charged Higgs and $\tan\beta$ is the limit[1] on the ratio $\tan\beta/m_{\mathrm{H}} < 0.27\ \mathrm{GeV}^{-1}$ obtained from an analysis of $B^+ \rightarrow \nu_\tau \tau^+$ decays collected by the L3 experiment at LEP [1] [2]. Previous analyses have also obtained $\tan\beta/m_{\mathrm{H}} < 0.67\ \mathrm{GeV}^{-1}$ from studies of the leptonic decays of the tau lepton [3], and $m_{\mathrm{H}} > [244 + 63/(\tan\beta)^{1.3}]$ GeV at a 95% confidence limit from an analysis of the $b \rightarrow s\gamma$ branching ratio [4]. Direct limits on the charged Higgs mass have also been set by CDF, D0, and the four LEP experiments[5, 7].

In the work presented here, we explore possible charged Higgs effects in $\tau^- \rightarrow \nu_\tau\,\mathrm{K}^-$ and $\mathrm{K}^- \rightarrow \bar{\nu}_l\, l^-(\gamma)$ decays. The branching ratios for these decay modes are well measured, and the Standard Model predictions are believed to be well understood.

2 Decays of the Tau Lepton and Charged Kaon in the Standard Model

The Standard Model prediction for the $\tau^- \rightarrow \nu_\tau\,\mathrm{K}^-$ branching ratio, including $\mathcal{O}(\alpha)$ electroweak corrections, is given by [8]

$$B(\tau^- \rightarrow \mathrm{K}^-\nu_\tau) = \frac{G_F^2 m_\tau^3 \tau_\tau}{16\hbar\pi} f_{\mathrm{K}}^2 |\mathrm{V}_{us}|^2 \left(1 + \frac{2\alpha}{\pi}\log m_{\mathrm{Z}}/m_\tau\right)\left(1 - m_{\mathrm{K}}^2/m_\tau^2\right)^2, \tag{1}$$

and the prediction for the $\mathrm{K}^- \rightarrow \bar{\nu}_l\, l^-(\gamma)$ branching ratio is [9]

$$B(\mathrm{K}^- \rightarrow l^-\bar{\nu}_l(\gamma)) = \frac{G_F^2 m_{\mathrm{K}} m_l^2 \tau_{\mathrm{K}}}{8\hbar\pi} f_{\mathrm{K}}^2 |\mathrm{V}_{us}|^2 \left(1 + \frac{2\alpha}{\pi}\log m_{\mathrm{Z}}/m_\rho\right)\left(1 - m_l^2/m_{\mathrm{K}}^2\right)^2. \tag{2}$$

Equation 2 is commonly used to derive the kaon decay constant, f_{K}, from the experimental measurements of the $\mathrm{K}^- \rightarrow \bar{\nu}_\mu\, \mu^-(\gamma)$ branching ratio, but the constant can also be obtained from lattice QCD calculations [10][11], or from other theoretical calculations, such as those based upon the relativistic constituent quark model [12][13].

3 Charged Kaon and Tau Decays in the MSSM

In theories where multiple Higgs doublets are responsible for spontaneous symmetry breaking of the electroweak interactions, charged Higgs particles arise as a natural consequence of the

[1] Unless otherwise specified, all limits presented in this note are the 90% confidence limits.

theory. These charged Higgs particles mediate charged current weak decays in the same manner as the $W^{\pm}$, only differing in the Lorentz structure at the decay vertex and in the coupling strength of the boson to the fermions. The MSSM predicts the existence of two Higgs doublets, where the first and second doublets couple to the up- and down-type quarks, respectively, and where the strength of the coupling to fermions is proportional to the fermion mass. The Standard Model branching ratios for the leptonic decays of the kaon and the decay of a tau to a pseudoscalar kaon are both modified in the MSSM by a multiplicative factor $\mathcal{R}_{\mathrm{H}}$[14][15] :

$$\mathcal{R}_{\mathrm{H}} = \left(1 - \frac{m_{\mathrm{K}}^2 \tan^2\beta}{m_{\mathrm{H}}^2}\right)^2 . \tag{3}$$

We obtain the charged Higgs mass limits by comparing the experimental world average $\tau^- \to \nu_\tau \mathrm{K}^-$ and $\mathrm{K}^- \to \bar{\nu}_l\, l^-(\gamma)$ branching fractions to the values predicted by Equations 1 and 2, multiplied by $\mathcal{R}_{\mathrm{H}}$[2].

4 The Kaon Decay Constant

We must ensure that the value of f_{K} used in these studies is not related to the measured $\mathrm{K}^- \to \bar{\nu}_l\, l^-(\gamma)$ branching ratios, and therefore independent from possible charged Higgs effects. We thus use f_{K} derived from lattice QCD calculations; to cancel many of the systematics associated with such calculations, we use the calculated ratio f_{K}/f_π multiplied by f_π determined from experiment [9]. The values of f_{K}/f_π determined by two independent lattice calculations are shown in Table 1. The value of f_{K} derived from the average of these results is $f_{\mathrm{K}} = 0.1552 \pm 0.0024$ GeV.

As a cross-check of the lattice calculational framework, we also examine the value of f_{K^*}/f_ρ determined by the same calculations. These results are also shown in Table 1, and are in agreement with each other, and also with the experimental measurement obtained from the $\tau^- \to \nu_\tau \mathrm{K}^*$ and $\tau^- \to \nu_\tau \rho$ branching fractions [18][19], $f_{\mathrm{K}^*}/f_\rho = 1.067 \pm 0.030$.

The kaon decay constant can also be derived from calculations based upon the relativistic quark model. The author calculates, using the formalism presented in reference [12], $f_{\mathrm{K}} = 0.1579 \pm 0.0044$ GeV, where the uncertainty is due to the uncertainties on the experimental values of inputs to the calculation. These inputs include the $\pi^0 \to \gamma\gamma$ branching fraction, the charged pion decay constant, and the K_{e3} form factor. Unlike the studies presented in reference [12], the inputs do not include the experimental value of f_{K}. The author's calculation of f_{K} is in agreement with the lattice results, and also with the result $f_{\mathrm{K}} = 0.155$ GeV presented in reference [13]. Reference [13] also estimates that the additional model dependent uncertainties on f_{K} are on the order of a few percent. In these studies, we thus choose to use the more precise lattice results, rather than this calculated value of f_{K}.

[2]It should be noted here that QCD and SUSY radiative corrections to $\mathcal{R}_{\mathrm{H}}$ are expected to be either small, or modify the factor in such a way that the limit on $\tan\beta/m_{\mathrm{H}}$ from this analysis would actually improve if they were included [16].

5 V_{us}

The most precise value of the CKM matrix element, V_{us}, is derived from experimental $\mathrm{K}^- \to \pi^- \bar{\nu}_\mathrm{e}\, \mathrm{e}^-$ results [17], and is relatively free from charged Higgs effects. The author finds, with calculations based on those presented in references [20] and [21], that the Standard Model $\mathrm{K}^- \to \pi^- \bar{\nu}_\mathrm{e}\, \mathrm{e}^-$ branching ratio is multiplied in the MSSM by a factor which is generally much closer to one than $\mathcal{R}_\mathrm{H}$, and thus charged Higgs effects on $|\mathrm{V}_{us}|$ are neglected here.

6 Fitting Procedure

To determine $\mathcal{R}_\mathrm{H}$ we minimise the χ^2:

$$\begin{aligned} \chi^2 &= \left(\frac{B^{\mathrm{WA}}_{\tau\to\nu\mathrm{K}} - \mathcal{R}_\mathrm{H} B^{\mathrm{SM}}_{\tau\to\nu\mathrm{K}}(\vec{X})}{\Delta B^{\mathrm{WA}}_{\tau\to\nu\mathrm{K}}} \right)^2 \\ &+ \left(\frac{B^{\mathrm{WA}}_{\mathrm{K}\to\bar{\nu}\mu} - \mathcal{R}_\mathrm{H} B^{\mathrm{SM}}_{\mathrm{K}\to\bar{\nu}\mu}(\vec{X})}{\Delta B^{\mathrm{WA}}_{\mathrm{K}\to\bar{\nu}\mu}} \right)^2 + \left(\frac{B^{\mathrm{WA}}_{\mathrm{K}\to\bar{\nu}\mathrm{e}} - \mathcal{R}_\mathrm{H} B^{\mathrm{SM}}_{\mathrm{K}\to\bar{\nu}\mathrm{e}}(\vec{X})}{\Delta B^{\mathrm{WA}}_{\mathrm{K}\to\bar{\nu}\mathrm{e}}} \right)^2 \\ &+ \sum_i \left(\frac{X_i^{\mathrm{WA}} - X_i}{\Delta X_i^{\mathrm{WA}}} \right)^2 , \end{aligned} \tag{4}$$

where $B^{\mathrm{WA}}_{\tau\to\nu\mathrm{K}}$ and $B^{\mathrm{WA}}_{\mathrm{K}\to\bar{\nu}l}$ refer to the world averages of the $\tau^- \to \nu_\tau\, \mathrm{K}^-$ and kaon leptonic branching ratios, and where $B^{\mathrm{SM}}_{\tau\to\nu\mathrm{K}}$ and $B^{\mathrm{SM}}_{\mathrm{K}\to\bar{\nu}l}$ are the Standard Model predictions for the branching ratios derived from Equations 1 and 2, respectively. Inputs to the predicted branching ratios, such as $|\mathrm{V}_{us}|$, the tau lifetime, etc., are contained in the vector $\vec{X}$; the vector $\vec{X}^{\mathrm{WA}}$ contains the world averages, while $\vec{X}$ contains the quantities allowed to float in the fit. Note that this approach ensures that the uncertainty on $\tan\beta/m_\mathrm{H}$ includes, in a natural way, the uncertainties on all of the quantities input to the fit. Unless otherwise specified, most of the inputs to the fit, such as lifetimes, and the meson and lepton masses, are taken from reference [9]. The least precise inputs to the fit are shown in Table 2.

The experimental world average branching ratios input to the fit are shown in Table 3. The kaon branching fractions are taken from reference [9], while the world average of the $\tau^- \to \nu_\tau\, \mathrm{K}^-$ branching fraction is derived from results presented in references [9] and [22].

7 Fit Results

The χ^2 fit using Equation 4 returns $\mathcal{R}_\mathrm{H} = 1.057^{+0.041}_{-0.039}$. Using the method presented in reference [23] to account for the unphysical region of $\mathcal{R}_\mathrm{H} > 1$, a limit of $\tan\beta/m_\mathrm{H} < 0.21\ \mathrm{GeV}^{-1}$ is determined at a 90% confidence limit. The limit as a function of the fit input value of f_K/f_π, along with its associated uncertainty, is shown in Figure 1.

The least precise outputs from the fit are shown in Table 2, and Table 3 shows the central values of the MSSM predictions for the branching ratios, as obtained from the fit results. The linear correlations between $\mathcal{R}_\mathrm{H}$ and the fit variables f_K/f_π, $|\mathrm{V}_{us}|$, and f_π are -80%, -55%, and -15%, respectively. When the fit is repeated, holding the values of all inputs fixed to the values returned by the first fit, the limit obtained is $\tan\beta/m_\mathrm{H} < 0.12\ \mathrm{GeV}^{-1}$.

Fitting only to the $K^- \to \bar{\nu}_\mu \mu^-(\gamma)$ branching ratio yields $\tan\beta/m_H < 0.21$ GeV^{-1}, while fitting only to the $\tau^- \to \nu_\tau K^-$ (or the $K^- \to \bar{\nu}_e e^-(\gamma)$) branching ratio yields $\tan\beta/m_H < 0.35$ GeV^{-1} ($\tan\beta/m_H < 0.45$ GeV^{-1}). Thus the combined limit on $\tan\beta/m_H$ is dominated by the result from the $K^- \to \bar{\nu}_\mu \mu^-(\gamma)$ branching ratio. However, the large tau samples expected to be collected by B meson factories such as Babar, Belle, and CLEOIII will dramatically improve the precision of the $\tau^- \to \nu_\tau K^-$ branching ratio, and thus improve the corresponding limit on $\tan\beta/m_H$, potentially rivaling the result obtained from the current value of the $K^- \to \bar{\nu}_\mu \mu^-(\gamma)$ branching ratio.

In addition, future improvements in the precision of inputs to the fit such as $|V_{us}|$ and f_K/f_π will also improve the limit on $\tan\beta/m_H$. It is possible that the value of $|V_{us}|$ extracted from the $\tau^- \to \nu_\tau K^*$ and $\tau^- \to \nu_\tau \rho$ decays expected to be collected by the B factory experiments will, when combined with the value of f_{K^*}/f_ρ from lattice calculations, rival the precision of the current value of $|V_{us}|$, especially if the precision of the lattice results also improves.

8 Conclusions

From a fit to the world average $K^- \to \bar{\nu}_\mu \mu^-(\gamma)$, $K^- \to \bar{\nu}_e e^-(\gamma)$, and $\tau^- \to \nu_\tau K^-$ branching ratios we determine $\tan\beta/m_H < 0.21$ GeV^{-1} at a 90% confidence limit. The area of the m_H versus $\tan\beta$ plane excluded by this, and previous indirect limits, is shown in Figure 2. The limit is expected to improve once precise values of the tau branching fractions are obtained by the various B factory experiments.

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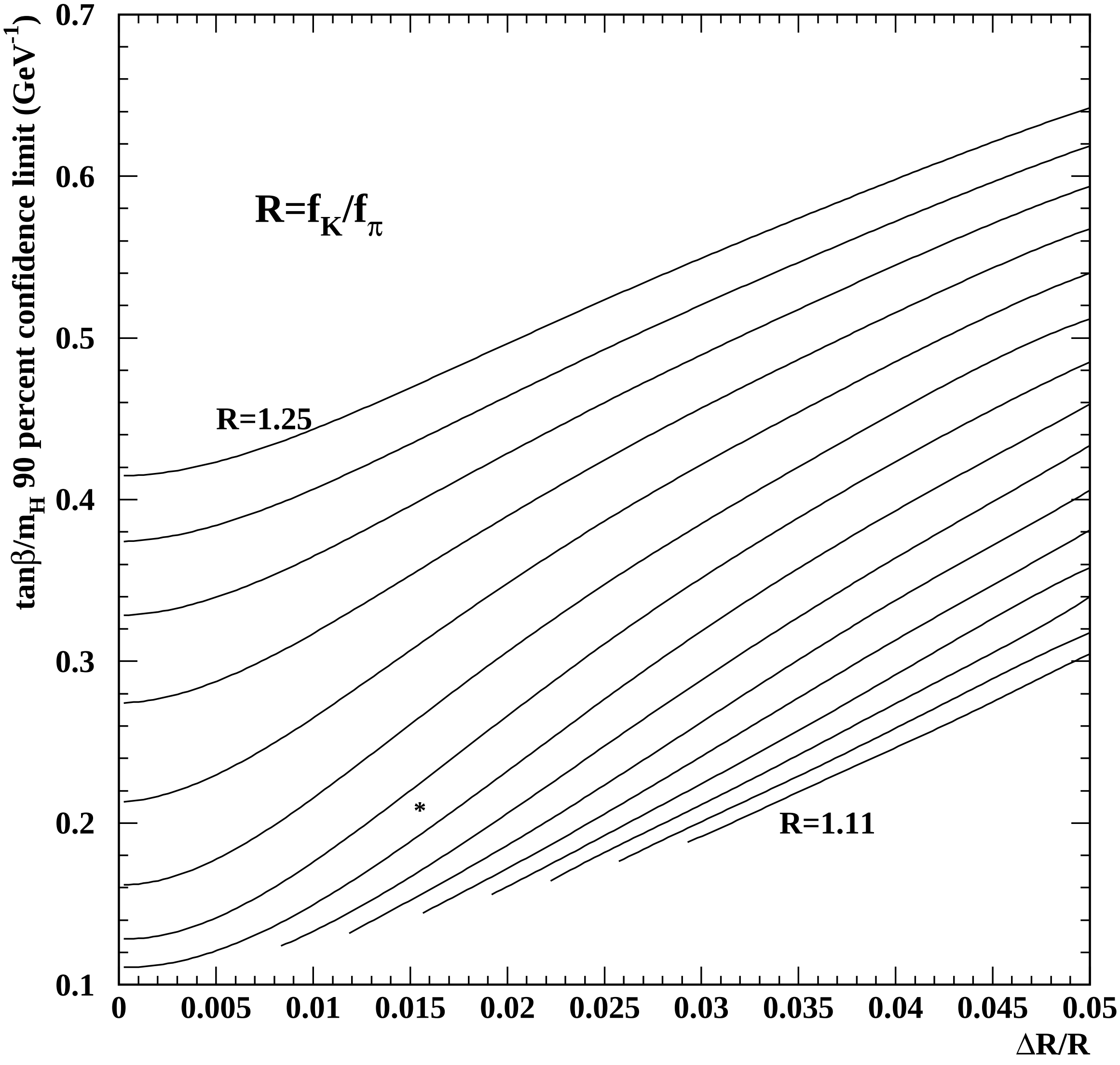

Figure 1: The 90% confidence limit on $\tan\beta/m_{\mathrm{H}}$ as a function of the fit input $R = f_{\mathrm{K}}/f_\pi$ and its associated relative uncertainty. The separate curves correspond to values of f_{K}/f_π from 1.11 to 1.25 in increments of 0.01. The $*$ indicates the limit set using $f_{\mathrm{K}}/f_\pi = 1.186 \pm 0.018$.

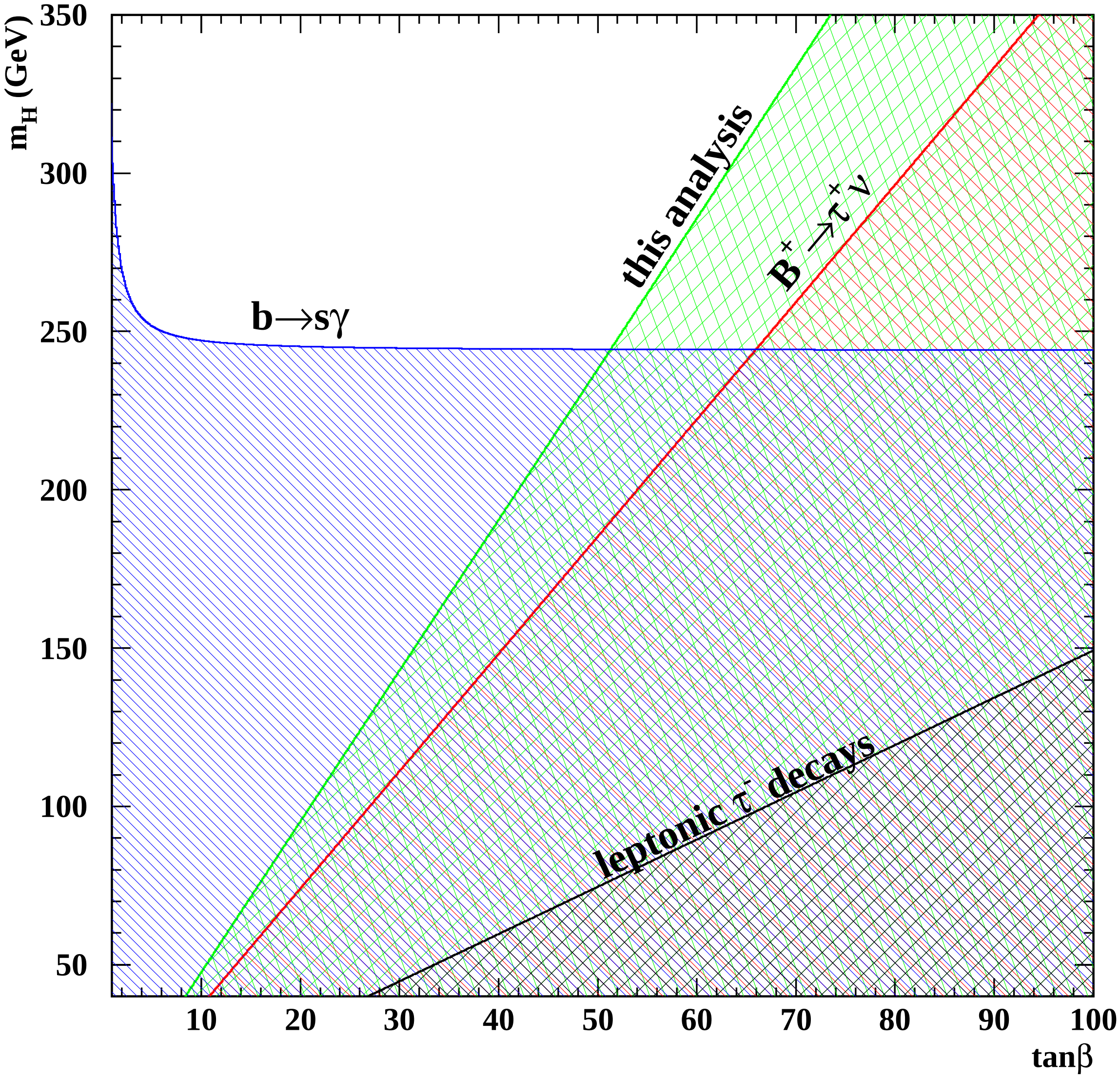

Figure 2: Indirect limits on tanβ and $m_{\rm H}$. The limit from $b \to s\gamma$ studies is the 95% confidence limit, while all other excluded regions reflect 90% confidence limits.

	f_{K}/f_{π}		$f_{\mathrm{K}^*}/f_{\rho}$	
Reference [10]	$1.20^{+0.03}_{-0.02}$		$1.06^{+0.01}_{-0.02}$	
Reference [11]	1.13 ± 0.04		1.10 ± 0.05	
Average and χ^2	1.186 ± 0.018	$\chi^2 = 2.5$	$1.061^{+0.010}_{-0.015}$	$\chi^2 = 0.9$

Table 1: Meson decay constants from lattice QCD calculations.

	input value		value from fit
$\lvert \mathrm{V}_{us} \rvert$	0.2196 ± 0.0023	[9]	0.2196 ± 0.0023
f_{π}	0.13070 ± 0.00039	[9]	0.13070 ± 0.00039
f_{K}/f_{π}	1.186 ± 0.018	see Table 1	1.186 ± 0.018

Table 2: Inputs to and outputs from the χ^2 fit.

	B^{WA}	$\mathcal{R}_{\mathrm{H}} B^{\mathrm{SM}}$
$\mathrm{K}^- \to \bar{\nu}_{\mu}\, \mu^-(\gamma)$	0.6406 ± 0.0018	0.6404
$\mathrm{K}^- \to \bar{\nu}_{\mathrm{e}}\, \mathrm{e}^-(\gamma)$	$(1.55 \pm 0.07) \times 10^{-5}$	0.1645×10^{-5}
$\tau^- \to \nu_{\tau}\, \mathrm{K}^-$	0.00694 ± 0.00027	0.00711

Table 3: World average branching ratios input to the χ^2 fit, and the central values of the predicted branching ratios, $\mathcal{R}_{\mathrm{H}} B^{\mathrm{SM}}$, returned by the fit.